NASA TT F-11,825

HIGH TEMPERATURE ENERGY SYSTEMS WITH PLASMA REACTORS AND INDUCTIVE MAGNETOPLASMA-DYNAMIC CONVERTORS

W. Peschka

Translation of "Hochtemperatur-Energiesysteme unter Verwendung von Plasmareaktoren und induktiven magnetoplasmadynamischen Wandlern"
Deutsche Versuchanstalt fur Luft-und Raumfahrt, Stuttgart, Institute fur Energiewandlung und Elektrische Antriebe, Sept. 1967, 25 pp.
Report DLR FB 67-59

N68-30811
(ACCESSION NUMBER) (THRU)
14 (PAGES) 1 (CODE)
1 (NASA CR OR TMX OR AD NUMBER) 25 (CATEGORY)
FACILITY FORM 602

GPO PRICE $ _____
CSFTI PRICE(S) $ _____
Hard copy (HC) 3.00
Microfiche (MF) .65
ff 653 July 65

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 June 1968

CONTENTS

Page

Introduction 1

1. Application of High Temperature Plasmas as Working Media. 2

2. The Plasma Reactor as a Source of Energy. 3

3. The Nuclear Fusion Reactor as a Source of Energy. 6

4. Summary 7

5. References. 8

6. Figures 9

HIGH TEMPERATURE ENERGY SYSTEMS WITH PLASMA REACTORS AND INDUCTIVE MAGNETOPLASMA-DYNAMIC CONVERTORS

W. Peschka

ABSTRACT. The purpose of this paper is to investigate possible future power generating equipment which operates with high temperature plasma as a working medium and subsequently with high power density. This temperature range requires reactors whose nuclear fuel is in the plasma state (fission or fusion reactors) coupled to magnetoplasma-dynamic generators acting as energy converters. Electrodeless MPD-Generators with all their advantages can be successfully employed. The technological ramifications arising from the application of these high temperatures with respect to the reactors and the MPD-Generators as well as to the heat release equipment are discussed.

INTRODUCTION

Prof. E. Knoernschild, Dr. of Eng.

The temperature ranges of modern energy generating equipment have constantly moved upward during the last decades. The reason for this tendency is the desire to increase the thermic efficiency of power plants, which can be successful, as is known, by chosing the highest possible upper temperature of the cycle at a given waste heat temperature. Today the temperature limits are essentially set by the consistency of the material of an energy system, i.e. by the walls, by the melting point of the nuclear fuel, the blade temperatures of gas turbines or the wall temperatures of magnetoplasma-dynamic exchangers. There is no doubt that the trend toward higher temperatures will continue in coming decades and that an attempt will be made to further increase the limits which up to now could be spoken of as the limits of solids. /7*

The possibility for a considerable advance into higher temperature ranges would be offered by an energy system whose nuclear fuel is present in a gaseous form which could then penetrate the temperature area between 5,000 and 50,000 °K. In this temperature range the working gases are already prevailingly ionized and interact very actively with electromagnetic fields. Hence the gases can be electromagnetically influenced, thus in our case electromagnetically enveloped, without the walls surrounding such an energy system, which have already been limited by admissible solid temperatures, becoming overloaded.

Up to the present time notions of this type have been considered Utopian and for this reason there exist only a few scientific works which

*Numbers in the margin indicate pagination in the foreign text.

attack these problems. The present work tries to give a survey of the possibilities of using the above-mentioned temperature range for the generation of energy. From the results of previous theoretical deliberations the conclusion can already be drawn that nuclear energy devices for this temperature range can be realized in combination with magnetoplasma-dynamic exchanger systems with a great expectation of success.

1. Application of High Temperature Plasmas as Working Media

The energy set free in nuclear fission and fusion processes is released, /8
as is known, at very high kinetic temperatures. They amount to about 90 MeV in nuclear fission and about 100 keV in nuclear fusion. Present day power systems are not capable of putting these high temperatures to work immediately. Since only solid systems have been considered in power plants up to the present time, it has been necessary to reduce the energy given off by nuclear energy generators until its temperature sinks to 2,000°K or to about 0.2 eV. This is a temperature range which can also be reached with chemical fuels. For reasons of good thermic efficiency, however, an essentially higher temperature would be worth working for. For technological reasons, particularly because of the solidity of the walls, temperatures over 2,000°K, however, are not very capable of being realized as long as the principle of a solid system is maintained. Particularly to utilize the highest temperature possible in solid systems, the idea exists of using magnetoplasma-dynamic (MPD) converters for changing heat energy into electrical energy, instead of steam or gas turbines. These are likewise limited to temperatures from about 2,000 up to a maximum of 2,500°K. At these temperatures, still very low for a plasma, the electrical conductivity, which represents an essential criterion for an efficient plasma generator, is still very small. To be sure with an input of alkali metals they can be brought to a range which can be considered as the lower boundary of meaningful operation of plasma converters, but then it is necessary to use converters with electrodes and the question of making the electrodes and walls of such a converter durable for long operating times must be faced.

Another type of converter, the inductive converter, in which the streams enclose themselves in the plasma and whose walls therefore do not serve for the introduction and evacuation of streams, requires a still much higher con- /9
ductivity, about 10 to 15 times higher as in the type with electrodes. It would naturally have the advantage of being able to keep the walls cool, since the plasma can be kept from the walls by means of magnetic confinement by an alternating field [7]. This offers the possibility of working in a temperature range of perhaps 5,000 to 20,000°K. The generation of a conducting plasma of this type (electron temperature 2-3 eV, electron density 10^{16} per cm^3) is, to be sure, not possible with current methods (chemical combustion, high temperature solid reactors). It assumes that the nuclear fuel is present in a gaseous form.

The use of this type of high temperatures naturally depends on the solution of the corresponding technological problems. As already mentioned, only the inductive MPD converter is suitable as an energy converter, because as a result of the magnetic alteration field in these converters there is no

immediate contact with the wall by the plasma. The confining activity of a magnetic alternating field (10^3-10^5 Hz) is especially effective in plasmas at high temperature, because only then are the streams produced in the plasma so strong that corresponding force activity can be effected. The electrical conductivity necessary for this (10^3 Siemens/m and more) is only reached at temperatures above 8,000°K. Thus on the one side the force acitivity on the plasma makes possible its containment, but on the other side an efficient generator operation. In addition it should still be noted that the containment of a plasma by a magnetic alternation field, in contrast to a magnetic constant field (kinematic containment by the gyration of ions and electrons around the lines of force), is also possible with large particle densities.

Thus if containment of high temperature plasmas in the inductive MPD generator seems possible, further research shows that for the generation of these plasmas it is necessary to have reactors whose nuclear fuel is in a plasma state. According to current knowledge, the nuclear fission reactor with fisionable material in the plasma state (called the short plasma reactor) and the nuclear fusion reactor are up for discussion; here the latter comes into consideration only as a remote goal. The condition that the nuclear fuel should be in the plasma state is given anyway for the nuclear fusion reactor (temperature about 10^8-10^9°K ca. 10-100 keV), while in the case of the nuclear fission reactor the operating temperature must be set so high that the fissionable material is in the plasma state. Characteristic of both sources of energy, as a result of their high operating temperature, is the fact that the energy flow (performance per throughput mass) surpasses conventional energy apparatus by orders of magnitude, so that comparatively essentially smaller throughput masses (g/MW) are necessary to approach the same performance level (Figure 1). On the one hand this simplifies the problem of implementing a closed thermodynamic process in the high temperature area and, on the other hand, permits a relatively small plasma density (about 10^{16}-10^{17} particles per cm^3) in the MPD generator as a consequence of the small throughput mass; this greatly simplifies control of higher plasma temperatures. /10

Below the plasma reactor as a source of energy will be considered first.

2. The Plasma Reactor as a Source of Energy

As already mentioned, the fissionable material for a plasma reactor is already in the plasma state. For reasons of neutron physics, such a reactor must be reflector moderated so that it can be made critical with the dimensions and pressures which are technically realizable [1, 2]. For years already research has been employed on this type of reactor, since it offered prospects of serving as an energy force for a nuclear jet power plant of a space vehicle where the jet mass, for example hydrogen, can be heated in such a reactor to high temperatures and expelled at a high rate of speed as a consequence of thermic expansion [3, 4]. A series of theoretical works has investigated the conditions under which such a reactor can become critical and what optimum reflector-moderator-configuration it must possess. Results have shown that it is possible in principle to make a plasma reactor critical in the temperature range from about 20,000°K with a pressure level between 20 and

1500 atm. and dimensions in the order of magnitude of meters. /11

Interest in such plasma reactors for driving purposes flagged after some time when it was shown that a basic problem, viz. the separation of the support mass (hydrogen, helium) from the fissionable material, is very difficult to solve [5, 6, 8]. But such a solution must be found so that the driving jet contains as little fissionable material as possible. From purely financial considerations the portion of fissionable material in the driving jet is permissible to a maximum of 10^{-3} at the most. Then the costs, because of the loss of fissionable material, amount to about the same as those which occur when a chemical system is used. If such a plasma reactor is used as an energy force in an energy system, this limitation would be omitted since no loss of fissionable material would occur as a consequence of the closed cycle. In this case, to be sure, allowance must be made for a "hot cycle" which presumes cheap and definite solutions and constructions, in which the interchangeability of the system as a unit must be required as an essential factor. The object of supplementary research should be to determine to what extent such solutions can be found. If it should be of interest to separate the fissionable material from the working medium even in a closed cycle, it can be easily accomplished up to a certain degree (1-3%).

Another very important problem which is of rather great importance in both the driving reactor as in the reactor furnishing energy inside an energy system, refers to the control of high plasma temperatures and the loads on the system walls associated with it. Theoretical research shows that of two possible kinds of energy flow, viz. heat transport by radiation and heat transport by conduction, heat conduction does not have to be considered in this temperature range in the first approximation. On the other hand energy transport through radiation is of greater significance. It appears that in the temperature and pressure range in question the plasma in the reactor is optically thick (here the optical depth amounts only to a few centimeters), so that it practically emits black radiation. If the radiation transport from a black /12
radiation plasma at a temperature of 20,000°K, which should prevail inside the reactor to a point near the wall, were to take place, the reflected energy would be far greater than that produced in volume.

Research at our Institute has shown that it is possible in principle to get a temperature profile of definite radiation between the edge and center inside such a plasma reactor, a temperature profile which resembles that in stars, i.e. consisting of a hot nucleus and relatively cool outer layers as formed in a star by the atmosphere and in a plasma reactor by the layers adjacent to the wall. This research has shown that it is possible in principle to maintain temperatures between 20,000 and 30,000°K in a plasma reactor in the pressure range of 30 atm. with a power density of about 500 MW/m^3 near the axis, while the temperature near the walldiminishes to about 8,000°K. This temperature of 8,000°K can be controlled by the means known up to the present time, such as drop in temperature in the boundary layer, injection cooling of the walls, etc., as follows from tests with high current electric arcs, etc. Let it be noted that in almost all published works on plasma reactors far too little attention has been given to the problem of optic radiation. The significance of energy transportation through radiation lies particularly in the

fact that it cannot be influenced by optically thick plasmas, as is possible in principle by magnetic alteration fields in the immediate convective transmission of energy to the wall.

Figures 2 and 3 show fundamental arrangements for getting energy with such plasma reactors and MPD generators as converters. In the reactor is found a suitable nuclear fuel, which heats a working medium (e.g. hydrogen, helium), which streams through the MPD segments by thermic expansion. The plasma in the MPD regions still consists partly of fissionable material, since a complete separation of the working medium from the fissionable material is not possible and, in contrast to a driving system reactor, is also unnecessary in a closed cycle. After the plasma in the MPD channel has given up part of its energy (alternating current, frequency 10^3-10^5 Hz.), the unconverted heat of /13
the plasma can be partly given off in the form of optic radiation in which the optical radiation is elevated with an admixture of heavy elements such as caesium, barium, etc. After further cooling recycling into the reactor takes place either in a liquid or gas form through a compressor injector. In this way current speeds between 10,000 and 20,000 m/sec can be attained in the MPD channel when hydrogen or even heavy hydrogen is used as a working medium, where the throughput mass is relatively small because of the high current speed and would amount to about 10 g/MW according to Figure 1. In this case the density of the plasma in the MPD channel would be tangibly less than in the plasma reactor, which both simplifies containment by the magnetic alternating field and also very greatly reduces the optic radiation in the MPD channel, because then the plasma in the MPD channel becomes optically thin. In a certain respect the conditions in this type of inductive MPD generator resemble the conditions which would occur in an inductive electrical drive plant in which a plasma of relatively small density is also used, which is not diminished as in the MPD generator but is brought to high speed in the MPD accelerator.

Here we mention some of the problems which must be clarified to decide whether such a system can be realized or not:

1.) The question of the critical dimensions of the reactor.

2.) The problem of the removal of the working medium from the reactor through a nozzle which in the present case can no longer be formed with mechanical walls but must be formed by magnetic alternation fields.

3.) Problems of the inductive MPD generator (in this area research is going on at the above-mentioned Institute).

4.) Emission of the unconverted heat.

Since the temperature in the MPD generator must not fall below 8,000°K, because then the conductivity of the plasma would become too low, the /14
unconverted heat must be emitted at a temperature of about 8,000°K. This can only take place through radiation from the plasma state. Therefore clarification is necessary about whether it is possible at all to realize "radiation coolers", in which the radiating elements are in the plasma condition (Figure 3). If these radiation coolers should be possible,

considerable amounts of energy could be emitted with very small cooling units. This is of significance above all when we think of constructing large energy equipment for space vehicles. But even for stationary applications the use of such a radiation cooler would be especially advantageous, since in this way the large amounts of heat can be radiated, not to the water of rivers or to the atmosphere (a problem which approaches us with further increase in power requirements), but by means of optic radiation through the atmosphere and out into space.

5.) Recovery of the ionization and dissociation energy in the cycle.

The cold working medium must be dissociated and ionized thermically when it is brought into the reactor, during which, in the case of hydrogen, an energy of 3.5 or 14 eV per molecule or atom must be expended. On the other hand the average thermic energy in the reactor only amounts to about 2 eV per particle. Therefore the entire efficiency of such a system would be too small, if the ionization energy and dissociation energy cannot be exchanged recuperatively, as illustrated in Figure 3. Such an exchange requires arrangements where heat is exchanged through the plasma state. How far this is possible must be shown by research. In general it appears that research work on a large scale on a complete series of areas is necessary before a conclusive judgment on the possibility of realizing such an energy system.

3. The Nuclear Fusion Reactor as a Source of Energy

The use of a nuclear fusion reactor as a source of energy could take place /15
in a form similar to that of the plasma reactor. The energy of heavy hydrogen would be transferred into kinetic energy by expansion in a magnetic nozzle, where the speed of the particles can lie in the order of magnitude of about 1,000 km/sec. as a result of the high reaction temperature in the nuclear fusion reactor (kinetic temperature about 100 keV) (Figure 4). This speed is already too high for discharge in an inductive MPD generator, since too high operating frequencies (in the area of several MHz) would be required for the tolerable construction length of the machine. For this reason the speed of the particles must be kept smaller, which seems possible either by mixing a colder medium (e.g. helium) or by removing material from the colder region of the nuclear fusion reactor. With this high speed (some 100 km/sec), the working gas is now able to emit power of the order of magnitude of many MW even with a throughput of fractions of a gram per second and even at low densities (10^{15} particles per cm^3) (Figure 5). With a throughput mass of 1 gram per second and a speed of about 100 km/sec, the power flow would be of the order of magnitude of 100 MW (see Figure 1).

The fact that such tiny throughputs of fractions of a gram are necessary shows that the problem of recycling the working medium for the purpose of closing the thermodynamic cycle practically poses no problems at all. When the working medium is cooled, e.g. by optic radiation, the decrease in volume of the gas is so great that only a relatively small amount of energy is

necessary for its recycling into the nuclear fusion reactor, even at high operating pressures. For example it would be possible to think of liquifying the heavy hydrogen and of reclaiming it again in a liquid form in the system. Since, furthermore, the density of the working medium in the MPD channel is essentially smaller than the density in the nuclear fusion reactor, there is no additional energy loss by deceleration radiation, as there will always be in the nuclear fusion reactor. Cooling the working gas after effective work performance in the MPD generator can take place in the form of optic radiation or cyclotron radiation; in the first case a heavy element is admixed with the working medium in order to raise the thermic radiation, and must again later be separated (Figure 5). /16

The thought may also occur that the working medium can again be recycled into the reactor after a short cooling period at a corresponding high temperature and conductivity with a MPD accelerator (pump) (Figure 6). Finally it can also be mentioned that only a few investigations on the exchange of energy delivered by a nuclear fusion reactor into electrical energy can be found in the literature. From the research going on at present, however, it can already be concluded that the inductive MPD system for realizing a nuclear fusion reactor would exactly produce a very good combination together with a system delivering energy.

Also of great importance is the nuclear fusion reactor as a driving reactor for space vehicles. Because of the high discharge rate of particles of the order of magnitude of 100 to 1,000 km/sec, attainable by thermic expansion, these particles can directly form the reactive jet of the drive plant, so that in this way a very effective drive can be obtained. In this case the inductive MPD generator cannot be rejected since it is needed to provide the necessary electrical energy for retaining the plasma in the nuclear fusion reactor. In this connection still another possibility for using an energy and drive system for space vehicles with the assistance of a plasma reactor, as treated in section 3, can be mentioned. With the aid of a plasma reactor and an inductive MPD generator connected to it, electrical energy can be generated which then accelerates the concomitant radiation mass in a MPD accelerator and produces a thrust. Since the performance level of a plasma reactor with an inductive MPD generator is very high (i.e. in the region from a few 100 to 1,000 MW), electrical drive plants with a strong thrust may be used.

4. Summary

The working temperatures of energy supplying equipment show a continual rise through the years. It is founded on the desire to constantly increase the thermic efficiency of such equipment. This tendency meets reactors, which work with gaseous nuclear fuels (plasma reactor), half-way. Hence the magneto-plasma-dynamic converter, whose working temperature will lie far above that of present day converters (gas turbines, steam turbines), presents itself as an energy converting system. /17

This report anticipates deliberations which will certainly be discussed on a broad front in the next fifty years, but whose significance will also be

recognized in our day.

Characteristic of energy supplying systems with maximum temperature plasmas is the fact that the power per unit of the throughput of the working medium is very high and, among other things, has the result that the containment of a thermodynamic cycle itself through the cryogenic state is expedient. Therefore the choice of the working medium is made tangibly freer.

A particularly attractive symbiosis of energy generator and energy converter is furnished by the nuclear fusion reactor, the energy conversion of which is best resolved by inductive magnetoplasma-dynamic systems.

High temperature energy conversion systems are promising for both the space flight sector and the area of terrestrial use. In the latter case it is particularly the large performances over 500 MW for which such equipment is particularly fit. Elimination of the need to provide for a drop in temperature in the cooling water of liquids may be an essential aspect in the future.

At the present time a conclusive judgment on the possibility of realizing this type of energy system can still not be made. For this a considerable amount of preparatory work in many fields of basic research, as well as in applied research, are still necessary. But one fact seems to be clear already /18 today, namely that the MPD converter will only come into its own range of action if an extreme temperature reactor, thus either a plasma reactor or a nuclear fusion reactor, is disposable as a source of energy flow.

REFERENCES

1. Safonov: Externally Moderated Reactors, Vol. 12, Reaktor Physics, Paper 625, /19 Sec. Un. Nations Int. Conf. on Peaceful Use of Atomic Energy, pp. 705-718, (Geneva), 1958.
2. Kikoin, K. et al.: Experimental Reactor with Gaseous Fissionable Substance (UF_6) "Soviet Jour. Atomic Energy," Vol. 5, No. 3, pp. 1167-1175, Sept. 1958.
3. Nelson, S.T.: The Plasma Core Reactor, ARS-Preprint 1734-61, May 3-5, 1961.
4. Spencer, D.F.: The Plasma Core Reactor, IPL TR-32-104, April 24, 1961.
5. Gross, R.A. and K.O. Kessey: Magnetohydrodynamics Species Separation in a Gaseous Nuclear Rocket, "AIAA-Journal," No. 2, p. 295, 1964.
6. Tumm, G.W.: Vergleichende Analyse von Gaskern-Reaktoren fur Antriebe von Raumfahrzeugen [Comparative Analysis of Gas Nuclear Reactors for Driving Space Vehicles], TU Berlin, Rep. No. 1, 1967.
7. Osovets, S.M.: Containment of a Plasma by a Travelling Magnetic Field, Plasma Physics on the Problem on Controlled Thermonuclear Reactions, Vol. VIII, 1958.
8. Bussard, R.W. and R.D. Delauer: Nuclear Rocket Propulsion, McGraw Hill Book Company, 1958.

(This list is far from complete; it should rather furnish appropriate indications).

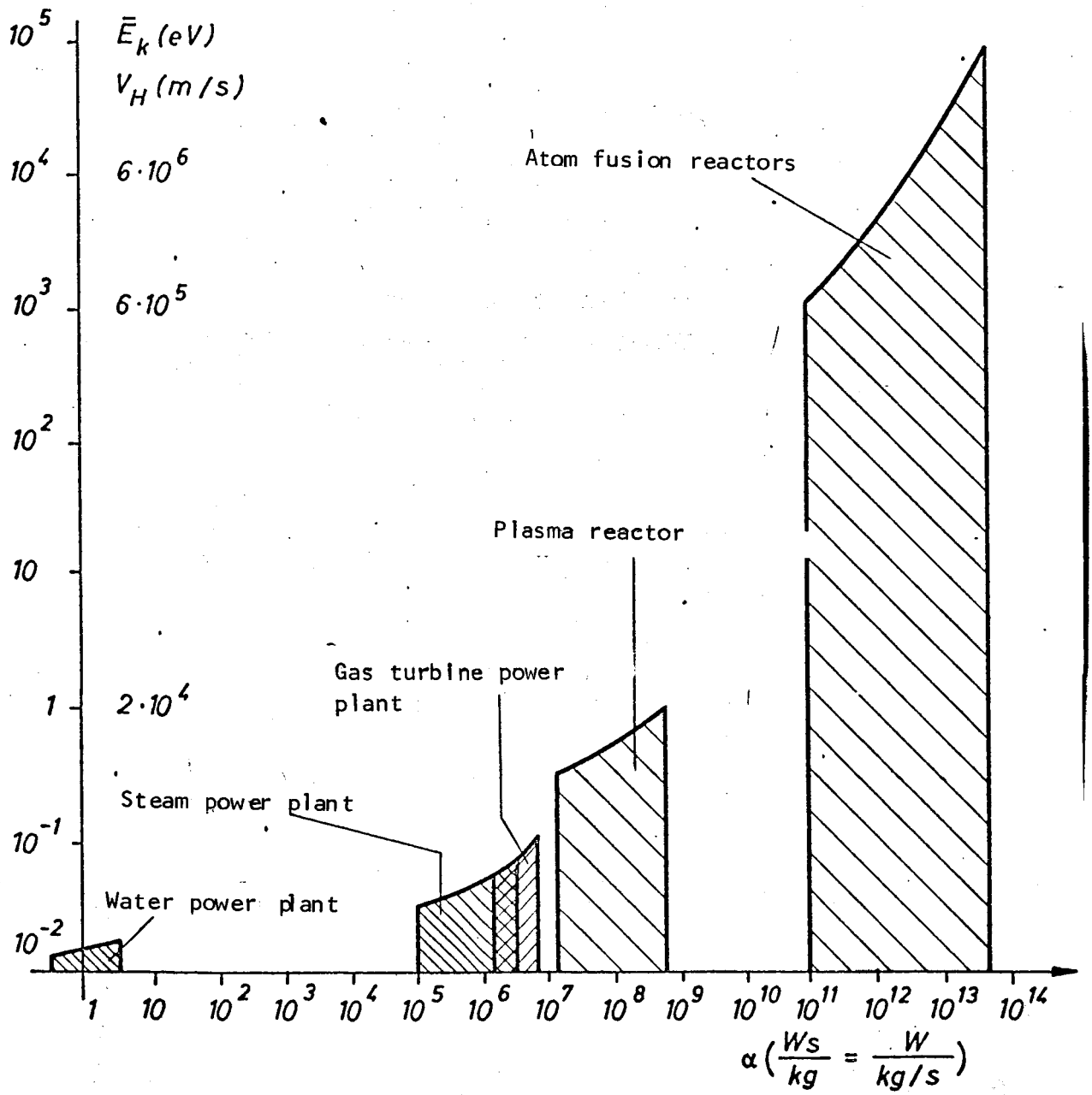
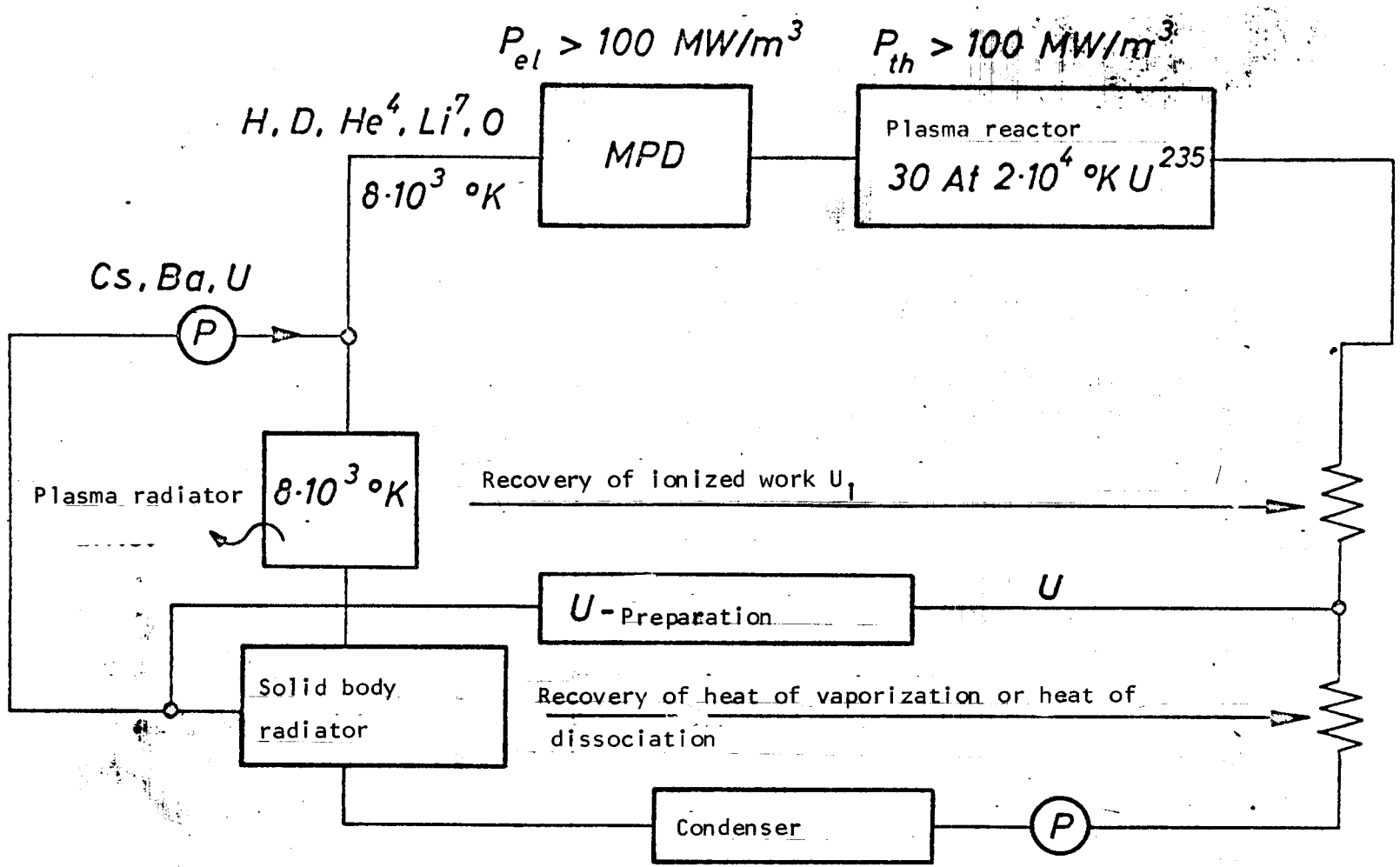


Fig. 1. Energy Flow $\alpha = \frac{N}{m}$ for Different Energy Generators as a Function of the Average Kinetic Energy $\bar{E}_k$ per Particle.



U_i = ionization work, α_V = heat of vaporization, α_D = dissociation energy

Li: U_i = 5,4 / 75,5 eV α_V = 5 kcal/g H: U_i = 14 eV α_D = 53 kcal/g He: U_i = 24 eV

Fig. 2. Principle of an Energy Recovery Device with a Plasma Reactor as the Energy Source and an Inductive MPD Converter. Feedback of the Working Medium Through a Pump in a Liquid or Gaseous State. (Rankine or Brayton Cycle).

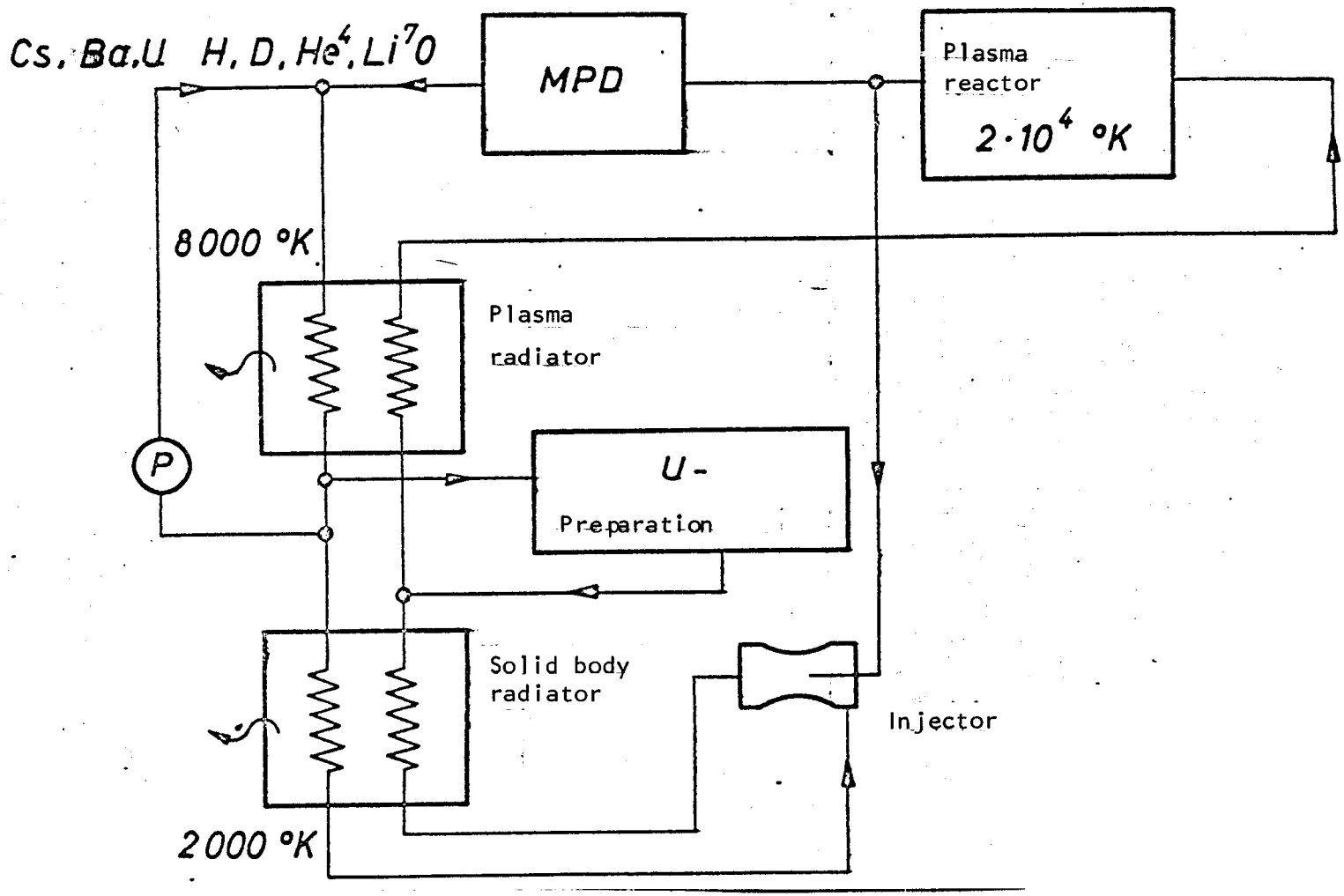


Fig. 3. Principle of an Energy Recovery Device with a Plasma Reactor as Source of Energy and an Inductive MPD Converter Feed-back of the Working Medium in a Liquid or Gaseous Condition through the injector.

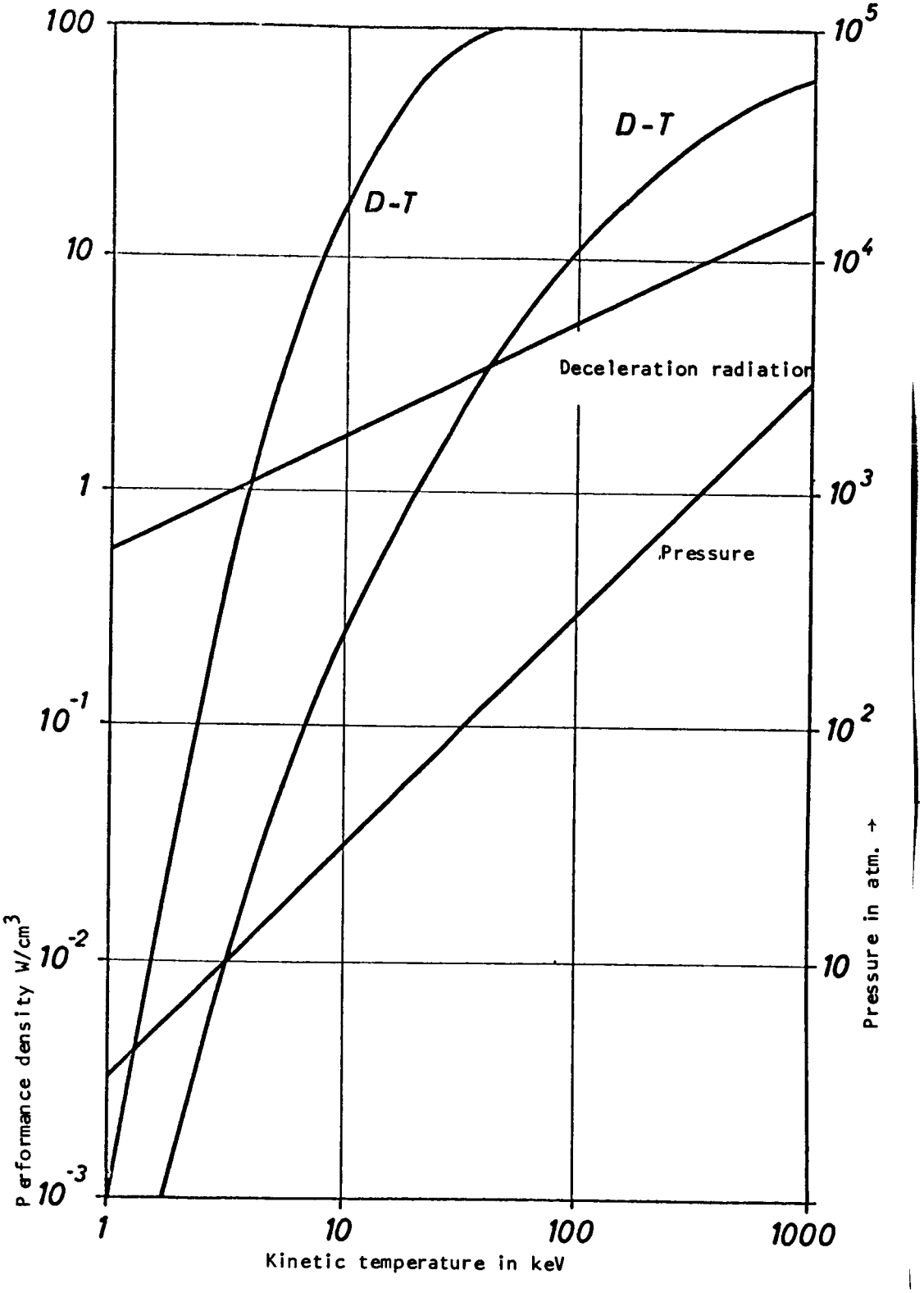


Fig. 4. Characteristic Thermonuclear Reaction and Ideal Ignition Temperature.

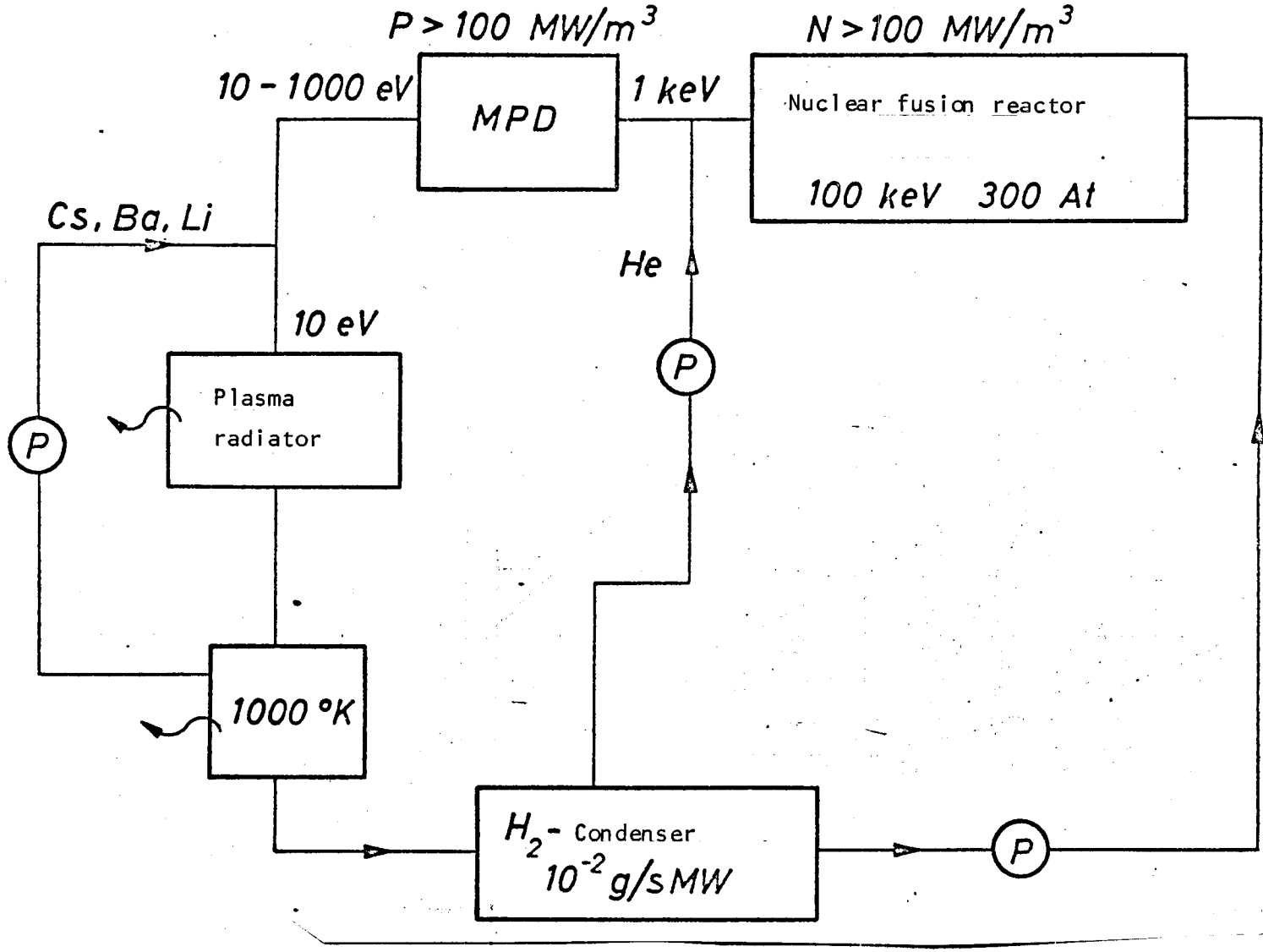


Fig. 5. Principle of an Energy Recovery Device with a Nuclear Fusion Reactor as a Source of Energy and an Inductive MPD Converter.

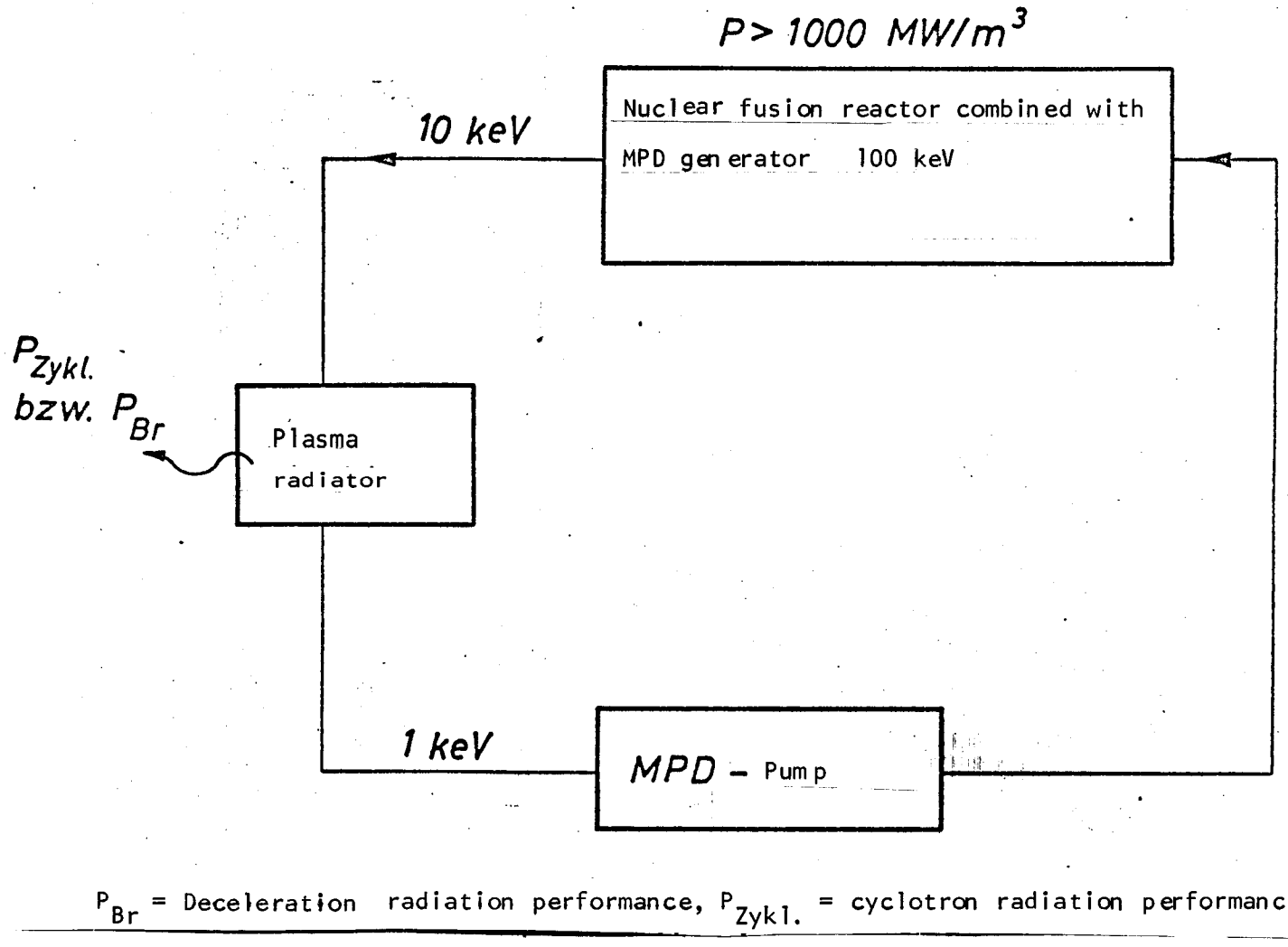


Fig. 6. Principle of an Energy Device Consisting of a Combination of Nuclear Fusion Reactor with an Inductive MPD Generator.